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(54) **Method for applying a barrier layer to a silicon based substrate and an article prepared in accordance with the method**

(57) A method for applying a barrier layer which comprises a barium-strontium aluminosilicate to a silicon containing substrate which inhibits the formation of cracks.

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Description

[0001] The present invention relates to a method for the preparation of an article comprising a substrate containing silicon and a barium-strontium aluminosilicate barrier layer which functions as a protective environmental/thermal barrier coating.

[0002] Ceramic materials containing silicon and metal alloys containing silicon have been proposed for structures used in high temperature applications as, for example, gas turbine engines, heat exchangers, internal combustion engines, and the like. A particular useful application for these materials is for use in gas turbine engines which operate at high temperatures in aqueous environments. By aqueous environment is meant a water and/or steam environment. It has been found that these silicon containing substrates can recede and lose mass when exposed to high temperature, aqueous environments. For example, silicon carbide when exposed to a lean fuel environment of approximately 1 ATM pressure of water vapor at 1200°C will exhibit weight loss and recession at a rate of approximately 6 mils per 1000 hrs. It is believed that the process involves oxidation of the silicon carbide to form silica on the surface of the silicon carbide followed by reaction of the silica with steam to form volatile species of silicon such as Si(OH)_x . It has been found that barium-strontium aluminosilicate barrier layer as a top layer is effective to reduce formation of volatile silicon species and thus reduce recession and mass loss. However, the barrier layer has been found to exhibit cracks in the fabricated matrix. Naturally it would be highly desirable to provide an external barrier coating for silicon containing substrates which is substantially crack free (cracks through the barrier layer to the substrate) and which would inhibit the formation of volatile silicon species, Si(OH)_x and SiO , and thereby reduce recession and mass loss.

[0003] Accordingly, it is the principle object of the present invention to provide method for the preparation of an article comprising a silicon containing substrate with a barium-strontium aluminosilicate (BSAS) barrier layer which is substantially crack free and which inhibits the formation of gaseous species of Si, particularly Si(OH)_x , when the article is exposed to a high temperature, aqueous environment.

[0004] It is a further object of the present invention to provide a method for producing an article as aforesaid.

[0005] The problems are solved by the teaching according to the independent claims. Particular developments are given in the dependent claims. Within the frame of the invention are all combinations of at least two of the descriptive elements and technical features disclosed in the claims and/or in the description.

[0006] The invention relates to a method for producing an article comprising a silicon containing substrate and a barium-strontium aluminosilicate barrier layer which is substantially crack free and which inhibits the

formation of gaseous species of silicon and/or provides thermal protection when the article is exposed to a high temperature, aqueous environment as defined above. In accordance with the present invention, the method comprises heating the silicon containing substrate to a temperature (T) of about greater than or equal to 1100°C, applying the barium-strontium aluminosilicate barrier layer to the substrate while the substrate is held at a temperature (T) of at least about 1100°C and thereafter holding the coated substrate at the temperature (T) for a minimum of at least about 15 minutes prior to cooling down the coated substrate to room temperature. The resulting article exhibits a substantially crack-free barrier layer having a crystalline structure of at least 80% by volume composed of celsian and hexacelsian phases. The nature of the crystalline phases depends on the time at temperature at which it is held. The barrier layer has a coefficient of thermal expansion which is compatible with that of the Si containing substrate prior to subsequent heat treatment.

[0007] In a preferred embodiment of the present invention the coated substrate is held for a time period of greater than or equal to 30 minutes.

[0008] In the frame of this invention the barrier layer comprises from about 0.10 mole to about 0.90 mole BaO and from about 0.10 mole to about 0.90 mole SrO, especially from about 0.25 mole to about 0.75 mole BaO and from about 0.25 mole to about 0.75 mole SrO. In a preferred embodiment the barrier layer comprises about 0.75 mole BaO and about 0.25 mole SrO. The coefficient of thermal expansion of the barrier layer should be within $\pm 3.0 \text{ ppm}^\circ\text{C}$ the coefficient of thermal expansion of the substrate or within $\pm 0.5 \text{ ppm}^\circ\text{C}$ the coefficient of thermal expansion of the substrate.

[0009] The method further includes the step of grit blasting the substrate -- at a preferred velocity of about 150/m/sec to about 200/m/sec -- prior to applying the barrier layer, preferably grit blast with alumina particles having a particle size of ≤ 30 microns.

[0010] The invention includes applying the barrier layer by thermal spraying.

[0011] At least one intermediate layer shall be applied prior to steps of

- heating the silicon containing substrate to a temperature T of greater than or equal to about 1100°C;
- applying a barrier layer comprising barium-strontium aluminosilicate to the silicon containing substrate at the temperature T to provide a coated substrate;
- thereafter holding the coated substrate at the temperature T for a time period of greater than or equal to about 15 minutes;
- cooling the coated substrate.

[0012] The at least one intermediate layer is selected from the group consisting of mullite and mullite-barium strontium aluminosilicate.

[0013] The at least one intermediate layer may comprise a bond layer of Si.

[0014] The bond layer shall be applied by heating the substrate to a temperature of at least about 800°C, applying an Si layer of a thickness of 3 to 6 mils and cooling the substrate to room temperature.

[0015] If two intermediate layer are applied, preferably a bond layer of Si is applied to the substrate and thereafter an intermediate layer, selected from the group consisting of mullite and mullite-barium strontium aluminosilicate prior to the afore-mentioned steps of the method.

[0016] The intermediate layer shall be applied by heating the substrate to a temperature of at least about 1100°C, applying the intermediate layer at the temperature T, thereafter holding the substrate at the temperature T for at least 15 minutes, and cooling the substrate to room temperature. And after step of cooling the coated substrate the cooled, coated substrate is heat treated at a preferred temperature of about 1250°C for about 24 hours.

[0017] The article prepared in accordance with the method can include one or more intermediate layers between the silicon based substrate and the barium-strontium aluminosilicate barrier layer, wherein said barrier layer has a crystalline structure of at least 80% by volume comprising celsian and hexacelsian phases. The intermediate layer(s) serve(s) to enhance adherence between the barrier layer and the substrate and/or to prevent reactions between the barrier layer and the substrate.

[0018] Further advantages, characteristics and details of the invention are apparent from the following detailed description of preferred embodiments of the invention with reference to the attached drawing..

[0019] Figures 1,2,3,4 show x-ray diffraction patterns of samples demonstrating the criticality of the holding time of the samples at elevated temperature after application of the barrier layer for obtaining a crystalline structure.

[0020] The present invention relates to a method for preparation of an article comprising a silicon containing substrate and a barium-strontium aluminosilicate barrier layer, wherein the barrier layer is substantially crack-free and inhibits the formation of gaseous species of silicon when the article is exposed to a high temperature, aqueous environment. The barrier layer may comprise a barium-strontium aluminosilicate barrier layer with or without intermediate layer as described below. In addition, it should be appreciated that while the barrier is particularly directed to an environmental barrier layer, the barrier layer also functions as a thermal barrier layer and thus the present invention broadly encompasses the use of environmental/ thermal barrier layers on silicon containing substrates and on substrates having comparable thermal expansion coefficients.

[0021] According to the present invention, the silicon containing substrate may be a silicon containing

ceramic substrate or a silicon containing metal alloy. In a preferred embodiment, the silicon containing substrate is a silicon containing ceramic material as, for example, silicon carbide, silicon nitride, silicon carbon nitride, silicon oxynitride and silicon aluminum oxynitride. In accordance with a particular embodiment of the present invention, the silicon containing ceramic substrate comprises a silicon containing matrix with reinforcing elements such as fibers, particles, and the like and, more particularly, a silicon based matrix which is fiber-reinforced. Particularly suitable ceramic substrates are a silicon carbide coated silicon carbide fiber-reinforced silicon carbide particle and silicon matrix, a carbon fiber-reinforced silicon carbide matrix and a silicon carbide fiber-reinforced silicon nitride matrix. Particularly useful silicon-metal alloys for use as substrates for the article of the present invention include molybdenum-silicon alloys, niobium-silicon alloys, and other Si containing alloys having a coefficient of thermal expansion compatible with the barrier layer of the present invention.

[0022] In accordance with the present invention, a barium-strontium aluminosilicate barrier layer is preferred with or without intermediate layers. A preferred barrier layer comprises from about 0.10 mole to about 0.9 mole, preferably 0.25 to about 0.75 mole BaO, 0.1 mole to about 0.9 mole, preferably 0.25 to about 0.75 SrO, 1.00 mole Al_2O_3 and about 2.00 mole SiO_2 wherein the BaO and SrO total is about 1.00 mole. A particularly suitable barrier layer for use on silicon containing ceramic compositions comprises about 0.75 mole BaO, about 0.25 mole SrO, about 1.00 mole Al_2O_3 , and about 2.00 mole SiO_2 .

[0023] It is an important feature of the present invention to maintain compatibility between the coefficient of thermal expansion of the silicon containing substrate and the barrier layer. In accordance with the present invention it has been found that the coefficient of thermal expansion of the barrier layer should be within ± 3.0 ppm per degrees centigrade, preferably ± 0.5 ppm per degrees centigrade, of the coefficient of thermal expansion of the silicon containing substrate. When using a silicon containing ceramic substrate such as a silicon carbide or a silicon nitride matrix with or without reinforcing fibers as described above in combination with the preferred barium-strontium aluminosilicate barrier layer of the present invention, it is desirable to develop a stable crystallographic structure in the barrier layer of the final article of at least 50% by volume celsian in order to obtain both structural integrity of the barrier layer and the desired thermal compatibility with respect to expansion coefficient between the silicon containing substrate and the barrier layer. The crystallographic structure of the barium-strontium aluminosilicate barrier layer is obtained as a result of the method of the present invention as will be described hereinbelow.

[0024] The barrier layer should be present in the

article at a thickness of greater than or equal to about 0.5 mils (0.0005 inch), preferably between about 3 to about 30 mils and ideally between about 3 to about 5 mils. The barrier layer may be applied to the silicon based substrate by any suitable manner known in the art, however, it is preferable that the barrier layer be applied by thermal spraying as will be described hereinbelow.

[0025] The article may include, in a preferred embodiment, one or more intermediate layers between the silicon containing substrate and the BSAS barrier layer. The intermediate layer(s) serve(s) to provide enhanced adhesion between the barrier layer and the substrate and/or to prevent reactions between the barrier layer and the substrate. The intermediate layer consists of, for example, SiO_2 , mullite, mullite-barium strontium aluminosilicate, mullite-yttrium silicate, mullite-calcium aluminosilicate, and silicon metal. It is preferred that the barrier layer comprises mullite-barium strontium aluminosilicate, mullite-yttrium silicate, or mullite-calcium aluminosilicate in an amount of between about 40 to 80 wt.% mullite and between about 20 to 60 wt.% barium strontium aluminosilicate or yttrium silicate or calcium aluminosilicate. The thickness of the intermediate layer is typical to those described above with regard to the barrier layer and the intermediate layer may likewise be disposed in any manner known in the prior art, however, preferably by thermal spraying as described hereinbelow.

[0026] In addition to the intermediate layer, a bond layer may be provided between the silicon containing substrate and the intermediate layer. A suitable bond layer includes silicon metal in a thickness of 3 to 6 mils. Alternatively, the silicon containing substrate may be pre-oxidized to provide a SiO_2 bond layer prior to application of the intermediate layer.

[0027] The method of the present invention comprises providing a silicon containing substrate and applying a barium-strontium aluminosilicate barrier layer (with or without intermediate layers) to the substrate wherein the barrier layer is substantially free of cracks to the silicon substrate and inhibits the formation of gaseous species of silicon when exposed to high temperature, aqueous environments. In accordance with the method of the present invention the substrate is heated to a temperature T of greater than or equal to about 1100°C, preferably greater than or equal to about 1200°C. The barrier layer comprising barium-strontium aluminosilicate is applied to the silicon containing substrate while at the temperature T to provide a coated substrate. In accordance with the preferred embodiment of the present invention the barrier layer is applied by thermal spraying. After application of the barrier layer to the silicon containing substrate at the temperature T, the coated substrate is maintained at the temperature T for a time period of greater than or equal to about 15 minutes, preferably greater than or equal to about 30 minutes, and ideally between 30 minutes and 1 hour. The

coated substrate is then cooled to room temperature. It has been found that the cooled substrate, prior to final heat treatment, has a crystalline structure of at least about 80% by volume comprised of celsian and hexacelsian phases. This crystalline structure is formed during the holding period of the coated substrate at the temperature T. Without the holding period, the resulting barrier layer is greater than 90% by volume amorphous. See Figure 4. It is the formation of the crystalline structure which is believed to result in a substantially crack free structure in the BSAS barrier layer of the composite material. The cooled coated structure is thereafter heat treated at a temperature of greater than or equal to about 1250°C for about 24 hours. The resulting composite has a barium-strontium aluminosilicate barrier layer having a celsian crystallographic structure in an amount of at least 50% by volume, preferably greater than at least about 80% by volume. The formation of the celsian crystallographic structure insures compatibility between the coefficient of thermal expansion of the silicon containing ceramic and the barium strontium aluminosilicate barrier layer as described above.

[0028] As noted above, one or more intermediate layers may be applied to the substrate. In accordance with the method of the present invention, a bond layer of Si may be applied to the substrate subsequent to heating the substrate and holding same at a temperature of at least about 800°C. When applying an intermediate layer comprising mullite or a combination mullite-BSAS, with or without a bond layer, the substrate is heated to a temperature of at least about 1100°C, the intermediate layer is applied at the temperature and the coated substrate is held at temperature for at least about 15 minutes prior to cooling to room temperature, preferably 30 minutes or longer, ideally 60 minutes or longer. The BSAS barrier layer is thereafter applied in accordance with the present invention.

[0029] The silicon containing substrate should be cleaned prior to application of the barrier layer to remove substrate fabrication contamination. It is preferred that the silicon based substrate be subjected to a grit blasting step prior to application of the barrier layer. The grit blasting step must be carried out carefully in order to avoid damage to the surface of the silicon-containing substrate such as silicon carbide fiber reinforced composite. It has been found that the particles used for the grit blasting should be hard enough to remove the undesired contamination but not as hard as the substrate material to prevent erosive removal of the substrate. Further, the particles must be small to prevent impact damage to the substrate. When processing an article comprising a silicon carbide ceramic composite substrate, it has been found that the grit blasting should be carried out with Al_2O_3 particles, preferably of a particle size of ≤ 30 microns and, preferably, at a velocity of about 150 to 200 m/sec. In addition to the foregoing, it may be particularly useful to preoxidize the silicon based substrate prior to application of the intermediate

and/or barrier layer in order to improve adherence. It has been found that bond layers of between 3 to 6 mils are preferred. SiO_2 bond layers of the desired thickness can be achieved by preoxidizing the silicon-carbide substrate at a temperature of between 800°C to 1200°C for about 15 minutes to 100 hours.

[0030] The silicon bond layer may be applied directly to the grit blasted surface by thermal spraying at approximately 870°C to a thickness of 3 to 6 mils.

[0031] Intermediate layers may be applied between the substrate and/or bond layer and the barrier layer or between the bond layer and barrier layer by thermal spraying in the same manner described above with respect to the barrier layer. As noted above, the preferred intermediate layers include mullite, mullite-barium strontium aluminosilicate, mullite-yttrium silicate, and mullite-calcium aluminosilicate.

[0032] After application of the desired layers to the silicon-based substrate material, the article is subjected to a heat treatment step in order to provide stress relief to the thermal sprayed structure, to promote bonding between the sprayed powder particles and between the layers and the substrate, and to develop the celsian phase in the BSAS barrier layer which is essentially amorphous in the as sprayed condition. The heat treatment step is carried out at a temperature of about 1250°C for about 24 hours.

[0033] The advantages of the article of the present invention will become clear from consideration of the following examples.

Example 1

[0034] Four samples of silicon carbide were heated to a temperature of 1100°F and a barium-strontium aluminosilicate layer was applied to the silicon carbide substrate at the temperature of 1100°F so as to deposit a BSAS barrier layer of 4 ± 1 mil in thickness on the substrate. The first sample was immediately cooled to room temperature. The second, third and fourth samples were held at 1100°F, after coating, for a time of 15 minutes, 30 minutes and 60 minutes respectively. Figures 1,2,3,4 show the x-ray diffraction pattern of each of the four samples after cooling to room temperature. It can be seen from the figures that the as-sprayed sample, not held for any time at the application temperature, is basically amorphous. The longer the sprayed sample was held at the elevated temperature, the greater crystallinity developed in the BSAS layer. In addition, the specimens of Figures 1a and 1c (specimens 1 and 3) were analyzed to determine the effect of the holding time on the quality of the barrier layer. The specimen of Figure 1 which was allowed to cool to room temperature immediately after cooling exhibited 9 cracks per linear inch in the barrier layer. Specimen 3, which was held at 1100°C after coating for a time period of 30 minutes was substantially crack free and exhibited 0 cracks per linear inch. Clearly, holding the specimen at the elevated tem-

perature of 1100°C after application of the barrier coating not only develops greater crystallinity in the BSAS layer but also substantially eliminates the formation of cracks in said layer.

[0035] This invention may be embodied in other forms or carried out in other ways without departing from the spirit or essential characteristics thereof. The present embodiment is therefore to be considered as in all respects illustrative and not restrictive, the scope of the invention being indicated by the appended claims, and all changes which come within the meaning and range of equivalency are intended to be embraced therein.

Claims

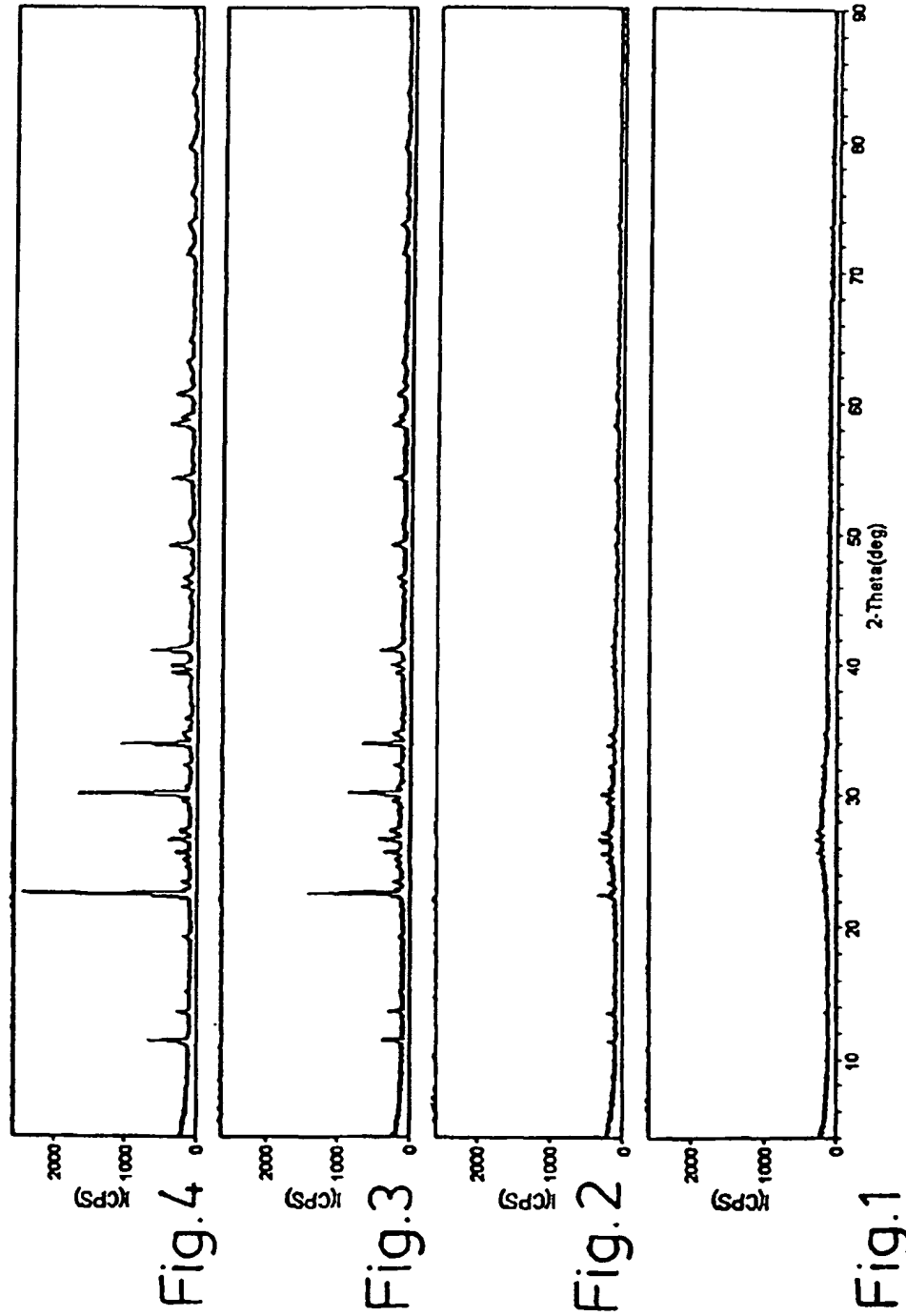
1. A method of preparing an article comprising the steps of:
 - (a) providing a substrate comprising silicon;
 - (b) heating the silicon containing substrate to a temperature T of greater than or equal to about 1100°C;
 - (c) applying a barrier layer comprising barium-strontium aluminosilicate to the silicon containing substrate at the temperature T to provide a coated substrate;
 - (d) thereafter holding the coated substrate at the temperature T for a time period of greater than or equal to about 15 minutes; and
 - (e) cooling the coated substrate.
2. A method according to claim 1 further including the step of heat treating the cooled, coated substrate.
3. A method according to claim 1 wherein the cooled coated substrate, prior to heat treating, has a crystalline structure of at least about 80% by volume.
4. A method according to claim 3 wherein the crystalline structure comprises celsian and hexacelsian phases.
5. A method according to one of the claims 1 to 4 wherein the coated substrate is held for a time period of greater than or equal to 30 minutes.
6. A method according to claim 1 wherein the temperature T is greater than 1200°C.
7. A method according to claim 2 including the step of heat treating the article at a temperature of about 1250°C for about 24 hours.
8. A method according to one of the claims 1 to 7 wherein the barrier layer comprises from about 0.10 mole to about 0.90 mole BaO and from about 0.10 mole to about 0.90 mole SrO, wherein especially

the barrier layer comprises from about 0.25 mole to about 0.75 mole BaO and from about 0.25 mole to about 0.75 mole SrO.

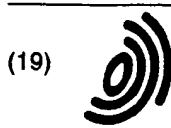
9. A method according to one of the claims 1 to 8 wherein the barrier layer comprises about 0.75 mole BaO and about 0.25 mole SrO. 5
10. A method according to one of the claims 1 to 9 wherein the coefficient of thermal expansion of the barrier layer is within ± 3.0 ppm/ $^{\circ}\text{C}$ the coefficient of thermal expansion of the substrate or wherein the coefficient of thermal expansion of the barrier layer is within ± 0.5 ppm/ $^{\circ}\text{C}$ the coefficient of thermal expansion of the substrate. 10
11. A method according to one of the claims 1 to 10 further including the step of grit blasting the substrate prior to applying the barrier layer, including preferably grit blast with alumina particles having a particle size of ≤ 30 microns. 15
12. A method according to claim 11 including grit blasting at a velocity of about 150/m/sec to about 200/m/sec. 20
13. A method according to one of the claims 1 to 12 including applying the barrier layer by thermal spraying. 25
14. A method according to claim 1 including the step of applying at least one intermediate layer prior to steps (b) through (e). 30
15. A method according to claim 14 wherein the at least one intermediate layer comprises a bond layer of Si. 35
16. A method according to claim 14 or 15 including applying the bond layer by heating the substrate to a temperature of at least about 800 $^{\circ}\text{C}$, applying an Si layer of a thickness of 3 to 6 mils and cooling the substrate to room temperature. 40
17. A method according to claim 14 wherein the at least one intermediate layer is selected from the group consisting of mullite and mullite-barium strontium aluminosilicate. 45
18. A method according to claim 14 including applying two intermediate layers, including preferably applying a bond layer of Si to the substrate and thereafter applying an intermediate layer selected from the group consisting of mullite and mullite-barium strontium aluminosilicate prior to steps (b) through (e). 50
19. A method according to claim 17 or 18 including 55

applying the intermediate layer by heating the substrate to a temperature of at least about 1100 $^{\circ}\text{C}$, applying the intermediate layer at the temperature T, thereafter holding the substrate at the temperature T for at least 15 minutes, and cooling the substrate to room temperature.

20. A method according to one of the claims 1 to 19 including after step (e) heat treating the cooled, coated substrate, including preferably the step of heat treating the article at a temperature of about 1250 $^{\circ}\text{C}$ for about 24 hours.
21. A method according to claim 19 or 20 wherein the cooled coated substrate, prior to heat treating, has a crystalline structure of at least about 80% by volume.
22. A method according to claim 21 wherein the crystalline structure comprises celsian and hexacelsian phases.
23. An article prepared in accordance with the method of at least one of the claims 1 to 22 having a crystalline structure of at least 80% by volume comprising celsian and hexacelsian phases.
24. An article comprising:
 - a substrate comprising silicon; and
 - a crystalline barium-strontium aluminosilicate barrier layer wherein said barrier layer has a crystalline structure of at least 80% by volume comprising celsian and hexacelsian phases.



X-ray patterns of thermal sprayed BSAS showing the development of crystallinity in the BSAS structure versus *in situ* hold at the thermal spray temperature of 1100°C after deposition but prior to first cooling to room temperature.



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EUROPEAN SEARCH REPORT

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DOCUMENTS CONSIDERED TO BE RELEVANT			
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The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 20 September 2001	Examiner Rosenberger, J
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**ANNEX TO THE EUROPEAN SEARCH REPORT
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This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
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